Using an Electric Resistance Tomograph to Detect Heartwood in *Eucalyptus globoidea*

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Date of Submission: 16/10/2020

Abstract

The focus of this dissertation was to determine whether or not using electrical resistivity tomography (ERT) was a viable option to replace destructive methods for measuring heartwood in *Eucalyptus globoidea.* The results from this analysis will be applicable to breeding trials conducted by the New Zealand Dryland Forests Initiative (NZDFI) relating to heartwood.

A few selected trees in two of the NZDFI breeding trails were felled and cross-sections were taken and stained to measure actual heartwood area to compare with estimated heartwood area from ERT scans taken before felling. Average heartwood area residuals were calculated to detect precision and bias in the results.

Previous tests of ERT have shown promise, with heartwood area of other species accurately predicted (R^2>0.80). However, the results of this research on *E. globoidea* showed that while the correlation between predicted heartwood area and actual heartwood area was strong (R^2=0.81), the relationship between the two variables varied with site. The standard error of a best-fit model including all these effects was 1.2 cm^2 on a range of predictions from 60 to 1600 cm^2. When site was not included as a random effect the standard error was 54.0 cm^2, and bias between sites was evident.

ERT measurements require calibration for each site and perhaps for each climatic condition. Further research required to test results across a larger range of sites and climates.

One of the main limitations of this study was the limited measurement heights, range of sites, and climatic conditions included. One of the sites was in flood during data collection, and the other main site was subjected to drought at the time of measurement. These factors likely had an influence on the results.

Acknowledgements

I would like to acknowledge my academic supervisor Euan Mason, for all the guidance he has provided throughout the research processing and offering me the opportunity to work on this topic to base my dissertation on. I would also like to acknowledge Luis Apiolaza for his support throughout the dissertation process and aiding in the statistical analyses involved.

I would also like to give a special thanks to PhD student Daniel Boczniewicz for allowing me to collect data during his research data collection and helping me with my own data collection. I would like to thank any of the other students or academic staff at the School of Forestry who have helped me along the way with any questions I might have had.

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1. Introduction

The most common objective of plantation forestry in New Zealand is to produce timber for structural use, with *Pinus radiata* being the main species. Radiata pine is a non-durable product, which must be treated with heavy metals, such as copper-chrome-arsenate (CCA) if it is to be used in outdoor settings. At this stage there is no better option for disposal of this treated timber than secure landfills (Rhodes 2013). There has been a push in the horticultural industry for more sustainable alternative durable timber, that does not have to be treated with CCA, to align with New Zealand's clean green image.

There is an estimated area of 1.5 million ha of *P. radiata* in New Zealand as of 2019 according to the National Exotic Forest Description (NEFD) (MPI, 2019). This large forest area of a single species plantation poses a great risk to the New Zealand forest industry as the threat of pest and diseases is much higher, and the introduction of a primary pathogen for radiata pine could have devastating consequences for the New Zealand economy. This is an additional motivation for creating a more diverse forest inventory in New Zealand.

Heartwood of some tree species is more naturally durable than sapwood, often reaching durability that would allow us to use it in contact with the ground with no preservation treatment. Natural durability is the resistance of wood to decay by fungi and insects. The heartwood often contains extractives which confer natural durability. There is a keen interest in durable heartwood species in New Zealand, especially naturally durable eucalypt species because they may reduce our reliance on treated timbers for posts, poles, and fencing uprights. Therefore, it is crucial to understand how heartwood develops in eucalypts and to find non-destructive ways to measure it accurately.

There are no published articles describing non-destructive methods to measure heartwood in eucalypts, and therefore the research described here was designed to test a method that exploits differences in electrical conductivity between heartwood and sapwood.

1.1 Background

1.1.1 New Zealand Dryland Forests Initiative

The New Zealand Dryland Forests Initiative (NZDFI) has been established to promote and research the possibility of growing naturally durable eucalypt in the drylands of New Zealand. The NZDFI was formed in 2008, with collaboration between the University of Canterbury, the Marlborough Research Centre, Proseed Ltd., regional councils and landowners around the eastern regions of New Zealand (NZDFI, 2020). They have received research grants from the New Zealand Government.

The NZDFI gathered information and analysed it to determine which durable eucalypt species have the best potential in the New Zealand dryland conditions. This information came from natural populations in Australia, pre-existing plantings in New Zealand, and other parts of the world where eucalypts have been adopted successfully. The five most promising eucalyptus species selected by the NZDFI are; *Eucalyptus argophloia, E. bosistoana, E. globoidea, E. tricarpa, E. quadrangulata.*

The long-term focus of this program is to produce superior genetic material ready for large-scale deployment and the establishment of a major hardwood resource in New Zealand. This will be completed through tree improvement of the selected species using established tree breeding methods, built around other breeding work with *P. radiata*, along with site selection, tending and growth and yield research.

The key target market in New Zealand for durable timber is posts for horticultural crops, such as; vineyards and kiwifruit orchards. Durable timber from eucalypts will ideally be able to replace CCA treated *P. radiata* posts. Other markets include decking, flooring, joinery and electricity cross-arms have potential as well. Moreover, testing is being conducted to produce laminated veneer lumber (LVL) from durable eucalypts. There is potential for eucalypt timber to compete with other species on hardwood markets.

1.1.2 Heartwood

The International Association of Wood Anatomists (IAWA) defines heartwood as the inner layer of wood in the growing tree that has ceased to contain living cells and in which reserve materials such as starch have been removed or converted into toxic substances generally referred to as extractives.

In addition to heartwood, trees contain sapwood. Sapwood is the outer wood; usually, a pale colour wood and heartwood is inner wood and usually is darker in colour. Depending on the desired end-product, sapwood or heartwood is more important and this is determined by what wood properties are required. Sapwood is considered less durable in outdoor settings, as it is more susceptible to insects and fungi and has a higher moisture content than heartwood without being treated.

There is a transition zone between the sapwood and heartwood that must be identified in order to accurately measure the area of heartwood in a cross-section, or the sapwood width as well. In some timbers, this transition zone is apparent due to the colour difference between sapwood and heartwood.

1.1.3 Electrical Resistance Tomograph

Electrical resistance tomograph (ERT) is a way of calculating the electrical resistivity of a number of resistance measurements made from electrodes placed in an arbitrary pattern (Kemna, Binley, Ramirez, & Daily., 2000; Daily, Ramirez, Binley, & LaBrecque.,2005). This method was originally developed to aid in geophysical problems, however, it has been utilized for several different applications to provide imaging of biomedical targets, rock fault investigation, groundwater table investigation, and soil moisture content to name a few. The theory behind the use of ERT is that different materials have varied electrical conductivity properties. When a current is passed through different materials, they will have different amounts of resistance to this current between the two electrodes, which is able to be measured and turned into either a 2D or 3D image.

1.1.4 Eucalyptus globoidea

Eucalyptus globoidea is commonly known as 'white stringybark' due to the stringy nature of the bark and is a species native through eastern New South Wales in Australia. It has a natural range from sea level up to 1100 metres and grows to a height of 30-40 metres tall. The natural form of the tree is typically a single straight leading stem and is self-pruning. The young leaves are a glossy green, with a lighter shade on the lower side. They have an egg-shape to lance-shape with a length of 40-100 mm and 20-45 mm wide. Adult leaves are the same shape, often curved and are glossy green on both sides. They have a length of 70-135 mm and are 12-40 mm wide. Flowers of *E. globoidea* are found in bundles of 11 to 15 on a flattened peduncle. The appearance of the timber is a dark brown/pink heartwood and a pale brown/pink sapwood. The texture is moderately fine with a straight grain. The timber is used in several different ways; structural, poles and posts, cross-arms, railway sleepers, vineyard and fence posts. In Australia, the timber is used for building framework (Bootle, 2005). Because of the attractive timber it has the potential as a flooring and furniture timber.

E. globoidea has been selected for NZDFI breeding trials as it grows well and consistently across a range of sites and its heartwood is a Class 2 durable timber, with a 15-25 year in-ground expected lifespan. *E. globoidea* has fewer problems with insect damage and possum browsing than many other eucalypt species.

This study was initiated in order to determine whether or not estimates of eucalypt heartwood area obtained using ERT were precise and unbiased enough to allow ERT estimates to be used in a breeding programme aimed at increasing volumes of heartwood produced by growing eucalypts with durable heartwood.

1.2 Literature review

1.2.1 Destructive methods used to measure heartwood

There are several ways to measure the amount of heartwood in a stem; however, most of these methods are destructive in some way. The most destructive method involves felling stems and then cutting cross-sections from the logs. One way to distinguish between the outer sapwood and the inner heartwood can be done by visual inspection of the colour difference within the wood, and the heartwood is typically darker in colour (Jorgensen, 1962) or by a chemical stain that is applied to the cross-sections. The chemical stain reacts differently with the extractives in each part of the wood to identify if heartwood is present (Bamber & Fukazawa, 1985). In some species, there is not always a clear colour difference between the sapwood and the heartwood, and a chemical stain must be used. Chemical stains detect heartwood because of the difference in pH between heartwood and sapwood. Typically the heartwood changes to a bright red/pink and the sapwood to a yellow colour depending on the stain used, which makes determinations of sapwood and heartwood more clear.

Another method which is similar to the one above involves extracting small wood cores from one or more places from a standing tree. This method is still destructive; however, it is less so as the tree usually survives cores being removed but it does add defects to the wood, which can decrease the quality of the wood from the tree. It also leaves the tree vulnerable to fungus growth, which can stain the wood. Heartwood and sapwood are identified in a similar way to the method above with visual inspection on the colour difference or by applying a chemical stain.

Microscopy or light table techniques give considerably different results from the staining method as they examine the wood for the presence or absence of tylosed vessels, and this method could be useful for sap flow measurements (Githiomi & Dougal, 2012). A similar method which was also developed more for sap flow measurements is dye perfusions which draw coloured dye through short sections of wood under vacuum. This process stains the conductive sapwood with dye, and all non-conductive areas are left unstained (Hoffman, 2012). Both methods are destructive as they both involve felling the stem and cutting cross-sections from it.

1.2.2 Electrical Resistance Tomography

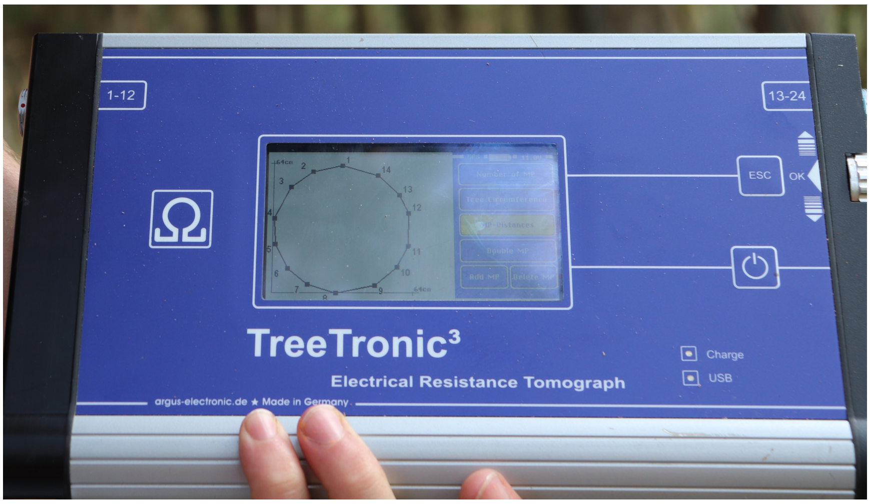


Figure 1: ERT in use during data collection.

A less invasive method is the use of electrical resistance tomography (ERT), which has been used to locate the sapwood-heartwood interface (Bieker & Rust, 2010; Guyot et al., 2013; Lin et al., 2012; Wang et al., 2016). This method works on the basis that most species have higher moisture content in the sapwood compared with the heartwood, which results in higher electrical resistivity in heartwood than sapwood. However, there are some other factors as well that affect electrical resistivity (Lin et al., 2012) as well and some exceptions in some tree species (Bieker & Rust, 2010).

One study concluded that the use of ERTs to evaluate the sapwood-heartwood demarcation of three different Asian gymnosperms was an effective non-destructive technique. The species used in this study were; Japanese cedar (*Cryptomeria japonica* D. Don), Taiwania (*Taiwania cryptomerioides* Hayata), and Luanta fir (*Cunninghamia konishii* Hayata). Their technique used a critical electrical resistance (ER) value that was established by the tomographic ERmax + ERmin value, and the sapwood-heartwood demarcation was the output of this calculation. The authors stated that electrical properties were affected by moisture content, extractives, temperature, pH, ion concentration, wood density, cell density, cell structure, tree defects and other factors in a standing tree (Lin et al., 2012). Therefore, it could be said that ERT is a useful way of measuring not only sapwood-heartwood boundaries but also tree growth performance in a non-destructive way.

Benson et al. (2019) calculated the sapwood area differently. They split each stained section and ERT into 16 sapwood radii. This method was used to better account for non-uniformity of the cross-section. They then used a calculation that first measured heartwood area, then took the sapwood area off. The sum of all sapwood areas gave the total sapwood area for a cross-section of wood. They found that the ERT method to be effective at identifying sapwood-heartwood boundary in *Quercus nigra* ($R^2 = 0.86$) and *Quercus virginiana* ($R^2 = 0.77$) and *Acer rubrum* ($R^2 = 0.73$).

Several studies have found that sapwood width measured with the staining method was actually 28% ± 3% higher than that of measured by ERT (Bieker & Rust, 2010; Rust, 1999; Wang et al., 2016). This is thought to be because the ERT shows the physiologically active sapwood, which is over-estimated by staining. In contrast to these findings, Benson et al. (2019) found that sapwood area was overestimated, however, there were strong ($R^2 \geq 0.80$) linear relationships between the ERT sapwood area and the measured conductive sapwood area.

Use of the ERT method has a number of advantages, including showing the entire cross-section compared with the coring method, which only takes specific measurement points. It does limit damage to a standing tree from the nail holes and therefore is non-destructive. Another advantage is the ease of moving the small device and setting it up and making a measurement takes between 15 to 30 min per tree (Bieker & Rust, 2010; Guyot et al., 2013; Lin et al., 2012; Wang et al., 2016) therefore you would be able to measure a large sample area in a relativity short amount of time. The process of making measurements is a complex set of operations and requires practice to take precise readings. One study found that working in pairs to be the most efficient way of making a measurement (Baláš et al., 2020). The ERT method has only been used on a small number of species, and so there is a chance to widen the research to other species such as eucalypt to validate its ability to evaluate the sapwood-heartwood demarcation.

1.2.3 Heartwood formation

Between the sapwood and heartwood is the transition zone, which is where heartwood formation occurs from in the inner sapwood. The heartwood transformation is indicative of a development process and not a deterioration of cell function with age, so the death of the parenchyma cells is the result and not the cause of heartwood formation (Bamber, 1976). This would explain why some older trees do not have any heartwood, and two stems of the same age can have different amounts of heartwood within their stems.

Fries and Ericsson (1998) and Ericsson and Fries (1999) suggested that breeding for heartwood was possible. They also stated that if a reliable ‘heartwood-meter’ becomes available that is non-destructive and quick to make measurements, then it makes it possible to breed for or against heartwood formation. This shows the need for a method similar to ERT which might be used in breeding trials.

1.2.4 Literature review conclusion

It is clear that there is a need for a non-destructive, and quick way to accurately measure sapwood-heartwood area. There are several different reasons why we need to know how much area there is. Therefore, it is important there is more time put into researching methods such as ERT. It could be an important tool in breeding programmes as it is non-destructive and it will make the selection properties easier to measure. As there is so much variability within species and between species, there is a need for more studies focused on expanding the number of species in which this method will work with.

2. Problem Statement and Research Questions

2.1 Problem Statement

Currently there is no way of measuring heartwood area and development without damaging trees in some way. This is a problem for breeding trials, such as the NZDFI trials, because breeders wish to breed for greater heartwood areas without removing or damaging superior trees. To test using ERT to measure heartwood, these measurements must be compared with one of the existing, reliable methods.

The objective of this dissertation is to aid breeding trials and the NZDFI to determine if the use of ERT through the use of the "TreeTronic" device, can accurately measure the area of heartwood in *E. globoidea* for selection of trees within breeding trials.

2.2 Research question

The research questions that aim to be answered in this dissertation are:

Can ERT measure the area of heartwood in *E. globoidea* with enough precision and small enough bias to be effective in breeding trials?

- Is there a strong correlation between the predicted area and observed area of heartwood?
- How biased is the predicted area?

3. Trial and Data Collection

3.1 Electrical resistance analysis

To undertake the ERT measurements the PiCUS TreeTronic (Argus Electronic GmbH, Rostock, Germany), which is a multichannel, multi-electrode electrical resistance tomograph, was used to perform the ERT analysis. The process of taking a measurement is as follows and is the same for each measurement point taken.

1. Tree height was taken with a vertex.
2. Measurement heights were marked on the stem of each tree along with a north point marked.
3. Electrically conductive nails were placed evenly around the plane of the measurement height, with measurement point one at north point using a hammer. A minimum of 8 nails was used, with up to 14 used on bigger stems. The nails were placed into the trees far enough to penetrate the moist wood past the bark. This was indicated by a change in tone when driving in each nail.
4. With the use of a measuring tape, the tree dimensions (circumference, distance between measurement points) were then logged into the TreeTronic device.
5. Electrodes that had crocodile clip-style were placed onto the corresponding nails.
6. The TreeTronic then placed an electrical current through each pair of electrodes. The current and voltage transmitted and received by each pair were recorded to form the measurement and then saved to the device.
7. Remove each nail and move to the next measurement point/next tree and repeat process.
8. The data was downloaded from the TreeTronic using the PiCUS software to form an ERT image. The image consists of a mesh of tessellating triangles, with each triangle having an electrical resistance value. For each ERT, a mesh fineness was set to 8 and smoothness to 20, the same as another study (Benson et al., 2019). These settings were chosen to minimise measuring errors.
9. ImageJ was used to process the measurement of each ERT scan. This method was chosen over other methods as clear heartwood boundaries were not always present in all cases and an estimation had to be made. Clear heartwood boundaries are required in order to use a code in R to measure heartwood area, such as the one used in the Benson et al. (2019) study.

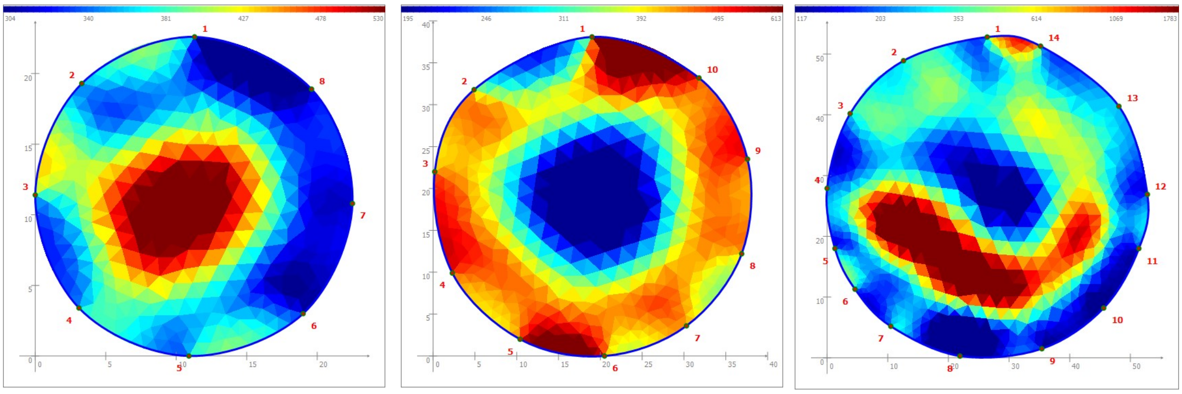


Figure 2: Examples of ERT scans taken during data collection.

3.2 Staining process

A pH indicator stain (dimethyl yellow) was applied to each cross-section with a brush. This process was completed either in the field or back in the laboratory. The stain once dry showed the heartwood to be a red/pink colour and the sapwood would be yellow in colour. After the stain was dry to the touch measurements were taken. The measurements recorded were; four bark measurements (cm), two total width measurements (cm), two sapwood length measurements (cm), and two heartwood length measurements (cm). Each pair of measurements were taken perpendicular to each other. All cross-sections were photographed with a scale directly after measurement were completed to be remeasured using ImageJ to calibrate results and measure heartwood area (cm^2).

Figure 3: Pre-staining of cross-sections in the field.

3.3 Trial sites and field measurements

This research employed recommendations from other studies (Benson et al., 2019), such as taking the scans at ground height (~40 cm), and DBH (diameter at breast height 1.4 m). Table 1 shows the complete list of measurements used to complete the analysis for this report. Maps of each site location can be located in the Appendix.

Millen:

The Millen site is in the Queen Charlotte Sounds, in the Marlborough district. The site is has a steep slope with a heavy understory. The site average site characteristics are:

The mean annual rainfall is 1700 mm and a mean annual temperature of 7°C (NIWA, 2020). On the day of measurement, the climate conditions were: 17°C with a humidity of 48% (Timeanddate.com, 2020). It was raining on and off throughout the day.

For the Millen site, one *E. globoidea* trees was selected and was approximately 14 years old. Three scans of this tree were taken (Ground, DBH, and 2.7 m) using the TreeTronic just before the tree was felled. The upper scan was completed using a pruning ladder to reach measurement height. The tree was then felled straight after, and cross-sections are taken at the locations of each scan from each tree. Tree height and DBH data were recorded prior to felling. The cross-sections were stored in a well-ventilated room until they were returned to the University of Canterbury to be placed in the freezer until staining could be conducted. The staining process used is described above.

MDC:

The MDC site is located just north of the town of Blenheim in the Marlborough district. The trees on this site were planted in 2009. It is on the flat and is on the border of the Wairau River and has the following site characteristics:

The mean annual rainfall is 650 mm and a mean annual temperature of 10.7°C (NIWA, 2020). On the day of measurement, the climate conditions were: 18°C with a humidity of 84% (Timeanddate.com, 2020). The site on the days of measurements had a high level of groundwater and was partly flooded.

At the MDC site, nine trees were scanned using the TreeTronic. Eight *E. globoidea* trees were scanned at ground level (~40 cm), and DBH, the final tree only a scan at ground level was taken. An upper measurement was not taken due to logistics and not having access to a ladder. The trees were felled the same day as the scanning. Cross-sections were taken from the eight trees at each scan location. The cross-sections were then stained straight away in the field and the same measurements taken as the Millen site. Tree height and DBH data were also recorded. Cross-sections were all photographed with a scale as well for the same process. ERT data was downloaded and processed using the PiCUS software. Images of the scans were measured using ImageJ.

Welcome Bay:

Welcome bay is close to Tauranga, in the Bay of Plenty and the trees were 20 years old. The site is on a slope with little to no understory. The average site characteristics are:

The mean annual rainfall is 1200 mm and a mean annual temperature of 8.4℃ (NIWA, 2020). On the day of measurement, the climate conditions were: 24℃ with a humidity of 76% (Timeanddate.com, 2020). The region this site was located in had been in a heavy drought for a number of weeks before measurements were taken.

At the Welcome Bay site, 12 *E. globoidea* trees were selected, and two scans were taken from each tree. The scans were taken at ground height (~40 cm) and DBH using the TreeTronic. Tree height and DBH data were recorded for each tree. The trees were then felled three days after scans were taken. Ideally, they would have been felled on the same day, however, this was not possible due to the logistics around personal who were experienced to fell the trees, and other data that had to be collected at the same time for other studies happening at the same time. Cross-sections were taken at scanning locations and stained straight away in the field. The same cross-sections measurements were taken as above. All cross-sections were then photographed with a scale for the same ImageJ process. ERT data was downloaded and processed using the PiCUS software. Images of the scans were measured using ImageJ.

3.4 Limitations:

The MDC site was partly flooded on the first day of data collection due to heavy rain earlier in the week, and this meant the groundwater levels were very high and could have an influence on the ERT scans. This site experiences periodic waterlogging due to its location as a reclaimed riverbank and proximity to the Wairau River.

The Welcome Bay site was subjected to drought for a number of weeks and during data collection. The scanned were also taken with on a particularly hot day. These climate conditions have the possibility of influencing the values recorded by the TreeTronic, but is unable to be verified as data was only collected during the same climate conditions.

Table 1: Table of tree data and measurement values

					Measured values		ERT values	
Tree ID	**Tree height (m)**	**Measuring height (cm)**	**Diameter (cm)**	**Mean bark thickness (cm)**	**Mean heartwood width (cm)**	**Heartwood area (cm2)**	**Mean heartwood width (cm)**	**Heartwood area (cm2)**
M_G1	20.90	40	38.38	4.18	30.54	503.52	28.62	539.35
		140	33.46	3.41	26.57	364.98	24.41	452.54
		270	29.86	3.15	23.53	283.65	22.23	373.72
B16_3	17.44	40	31.23	2.75	17.16	289.55	19.26	260.35
		140	25.95	2.33	16.43	224.61	18.52	242.78
B15_4	18.87	40	23.90	2.08	15.42	177.60	24.54	434.24
		140	23.54	1.65	14.45	166.34	18.77	287.73
B13_18	19.05	40	38.43	2.28	24.57	516.60	23.15	385.57
		140	29.67	1.65	19.54	313.86	17.70	250.03
B14_7	11.56	40	28.30	3.90	16.21	177.11	17.35	211.09
		140	24.59	3.40	12.88	122.24	13.60	137.20
B61_2	12.08	40	22.32	2.15	13.45	139.81	19.07	302.29
		140	24.23	2.20	13.93	144.58	18.33	229.90
B1	12.48	40	24.78	3.50	14.02	150.06	18.68	251.65
		140	25.90	2.93	15.57	188.63	20.66	370.28
B5	11.59	40	16.54	3.95	9.19	66.57	16.46	181.18
		140	17.97	3.05	9.91	76.70	12.39	88.20
B3	12.48	40	29.61	3.53	17.51	241.05	18.96	331.40
W_1	30.40	40	42.51	6.25	35.64	961.86	39.95	1126.90
		140	38.22	5.75	30.45	737.56	37.68	981.16
W_2	28.24	40	35.80	3.00	27.71	683.53	27.63	519.92
		140	33.86	2.50	26.31	563.59	22.34	361.66
W_3	29.91	40	42.13	5.23	33.99	914.36	21.89	374.36
		140	41.48	4.70	33.72	861.22	19.43	335.83
W_5	31.11	40	42.23	4.10	35.14	1171.95	31.66	736.63
		140	40.60	3.70	35.70	1022.34	25.58	539.33
W_7	29.23	40	38.17	5.25	32.90	876.21	34.03	1002.52
		140	34.35	5.00	28.37	620.74	23.09	492.89
W_9	31.03	40	43.78	4.25	36.03	1014.58	26.83	728.78
		140	38.96	4.38	31.77	804.55	24.15	474.23
W_10	28.03	40	38.44	4.75	32.53	820.37	27.51	553.07
		140	36.61	4.65	28.96	662.33	26.18	531.32
W_11	27.71	40	37.83	7.50	28.06	624.56	30.38	720.86
		140	34.11	5.50	25.44	488.95	23.41	536.67
W_12	32.28	40	56.37	5.63	46.02	1576.77	40.34	1338.19
		140	50.01	4.75	41.07	1313.21	33.84	895.45
W_13	26.02	40	42.63	4.13	33.43	883.72	26.52	495.26
		140	40.22	3.38	31.09	755.57	23.73	528.13
W_14	28.28	40	31.64	4.05	25.69	524.90	18.68	240.90
		140	30.72	3.50	23.81	437.72	19.11	266.53

4. Methods of Analysis

4.1 Residual analysis

All data that were collected was analysed using the statistical software R (R, Version 4.0.2; RCore Team, 2020). The heartwood area residuals were calculated by subtracting the predicted values (ERT) from the observed values (Cross-section). The residuals were then plotted against several variables, such as bark thickness and stem diameter. This was used as an initial check for bias in predicting heartwood area values.

4.2 Modelling of observed and predicted values

A linear mixed-effects model was used to see how well the predicted values compared with the observed values for each site, with the first model being:

$$\gamma = \mu + area + site + \varepsilon$$

Where γ is the observed heartwood area, μ is the mean of the heartwood area, area refers to the predicted heartwood area from the ERT measurement, site refers to the effect on site on the heartwood area and ε is the residual error. This model was adapted in order to improve the residual standard error and will be shown in the results section of this report. Site was employed as a random effect and all other terms were fixed effects.

Another model was fitted to include the effect of the tree height on the predicted value using each tree ID and site as a random effect, which was:

$$\gamma = \mu + area + tree\ height + \ \varepsilon$$

This model was used if the predicted heartwood area was able to be modelled in order to calibrate the estimated results. This model was adapted and all the predictor factors that may influence the predicted heartwood area were tested, in order to improve the residual standard error and fit the best model possible. A 95% confidence interval was used for the analysis completed.

5. Results and Discussion

5.1 Residual analysis

To begin the analysis, the first step was to plot the actual heartwood area values, measured from the cross-sections against the predicted heartwood area from the ERT measurements. The Millen site and the MDC site were merged to create two overall environments of data points. This was done as data points from the Millen site showed a similar trajectory to the MDC site and with a limited number of data points made the remaining analysis more clear. Figure 4 shows that the data had a linear overall shape, with the two smooth lines for each site. However, it also illustrates that there was a clear difference between the two sites, and each site had a different intercept.

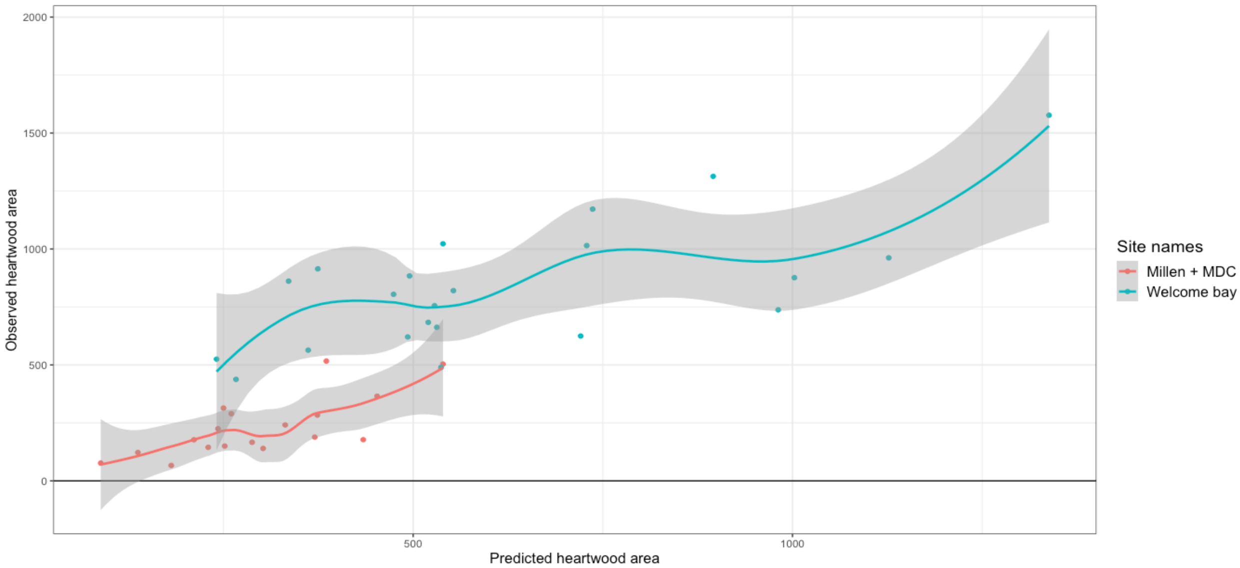


Figure 4: Observed heartwood area plotted against predicted heartwood area from ERT measurement.

The first variable that was compared with average heartwood area residual was the predicted heartwood area, with each data points identified by site. Figure 5 shows an interesting site split in predicted heartwood area. The Millen and MDC sites are shown here to have a negative bias towards the predicted heartwood area. The result of this bias for these sites means that heartwood area is being overpredicted, and in once case by 250 cm^2.

At the Welcome Bay site there is a greater amount of variation in the residuals, however, this is likely a result of the limited number of data points and any single data point has a larger effect on the variation. The majority of the biases from this site were positive, which indicates that ERT heartwood areas estimates underestimated actual heartwood area. There were two data points that underestimated the observed value by more than 500 cm^2.

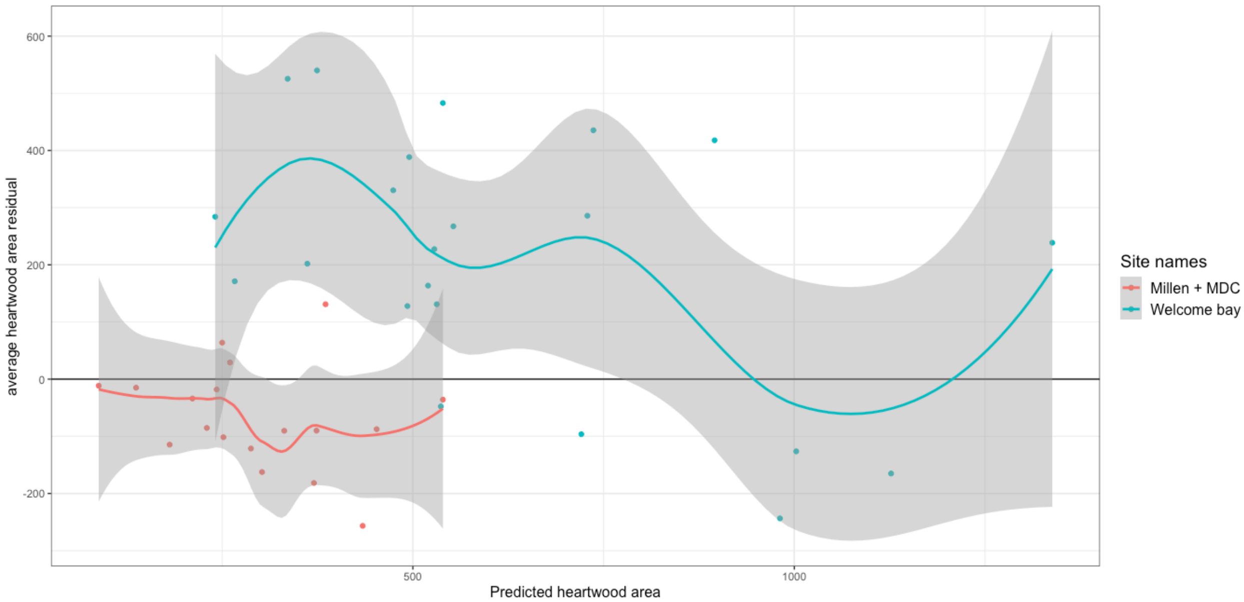


Figure 5: average heartwood area residual against the predicted heartwood area, split by site.

The next check for the residual analysis was to plot average heartwood area residual against predicted heartwood area, with each data point separated by measurement height. Figure 6 illustrates that measurement height made little difference to the residuals.

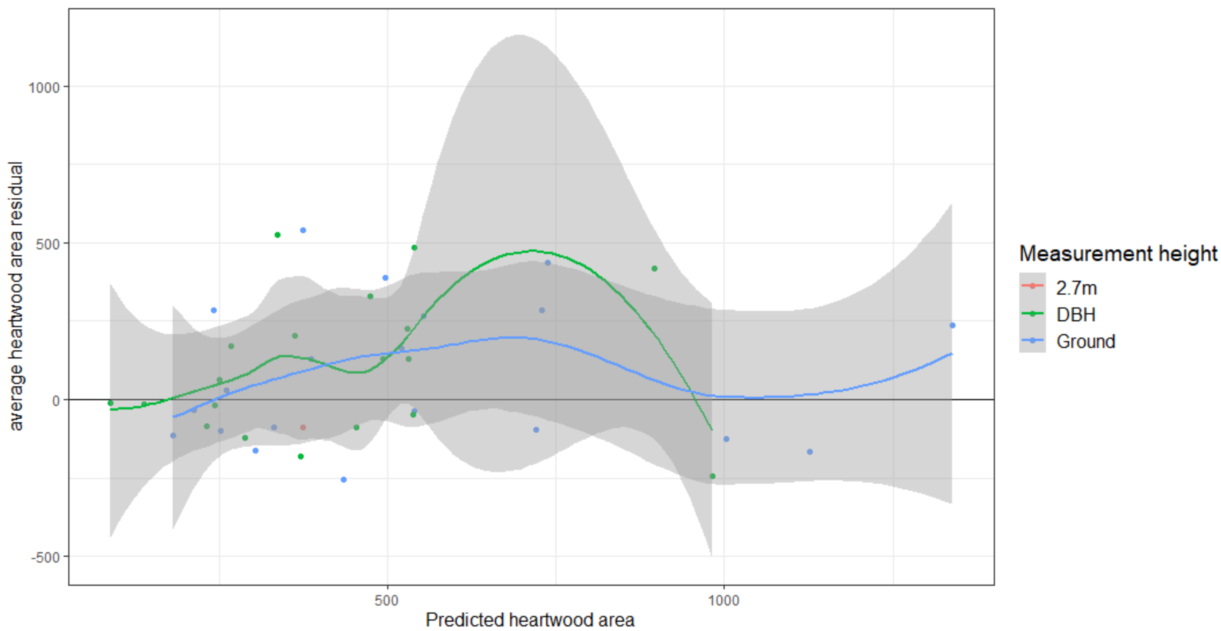


Figure 6: average heartwood area residual against predicted heartwood area, split by measurement height.

The next step was to plot residuals versus stem diameter of the measurement point. Figure 7 shows the average heartwood area residual against stem diameter, separated by site. The overall tread is that smaller diameters tended to show negative bias, and the larger diameters to display positive bias. As above, this indicates that smaller diameters had heartwood area overestimated, and the larger diameters had heartwood area underestimated by the ERT.

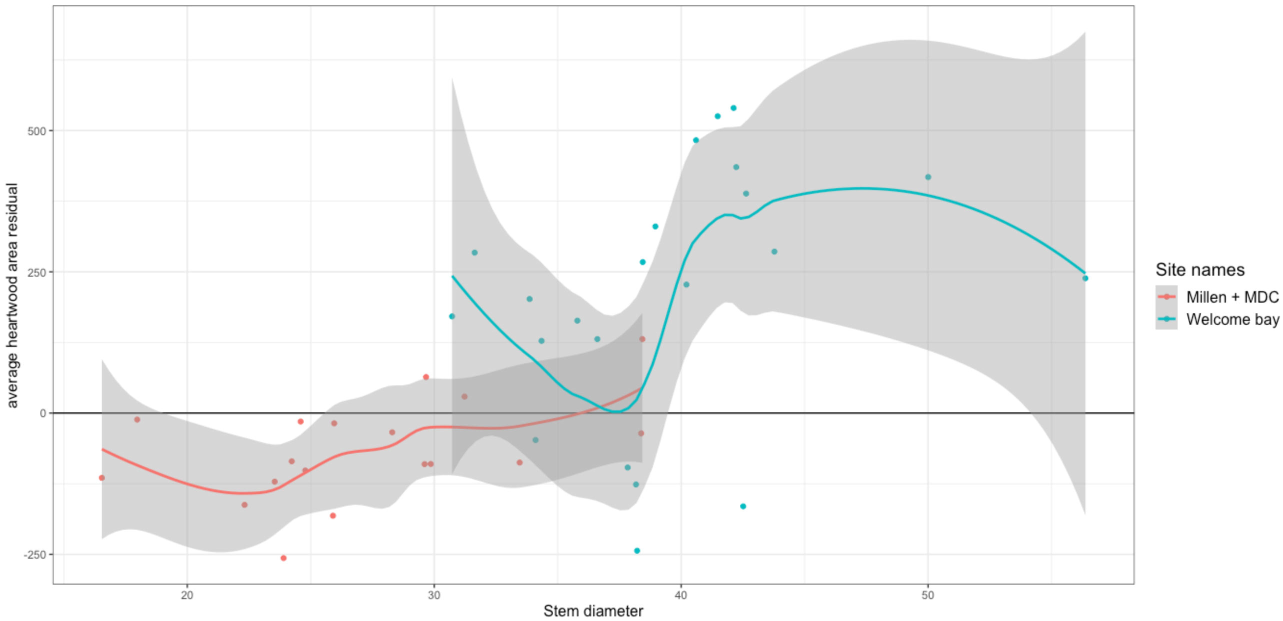


Figure 7: average heartwood area residual against predicted heartwood area, split by site.

The final check for the residual analysis was to plot the average heartwood area residual against the average bark thickness of each measurement point. Figure 8 displays similar results to the previous figures, and the trends are the same larger stem sections with thicker bark had underestimates and smaller stem sections had overestimates of heartwood with the ERT, but as larger stem sections came from one site while smaller sections came from the other site the causes of the bias could not be clearly distinguished.

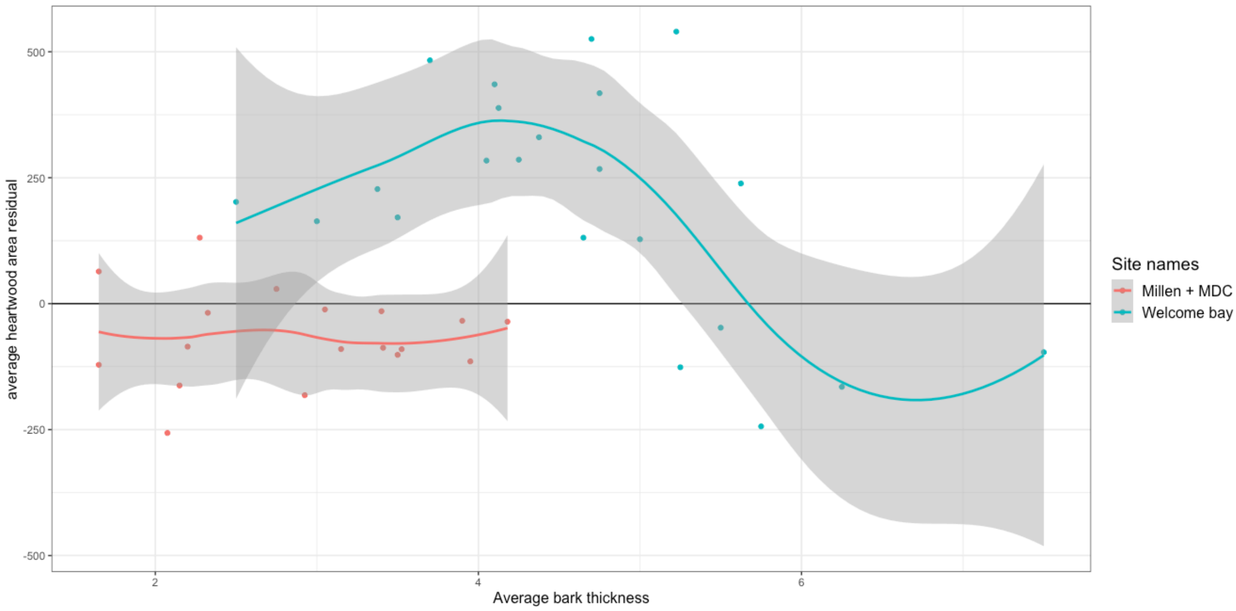


Figure 8: average heartwood area residual against predicted heartwood area, split by measurement height.

5.2 Multiple regression models

Model 1

In the first linear model observed heartwood area was modelled as a function of the predicted heartwood area with site as a fixed effect. As above, the Millen and MDC site were merged. The interaction between site and predicted area was checked and the p-value was above 0.05, therefore showing no difference in slope of the relationship between actual heartwood area and ERT estimates between sites.

Table 2 Interaction check between predicted heartwood area and site.

	Estimate Std.	Error	t value	Pr(>|t|)
Heartwood area ERT: Site	-0.1645	0.3728	-0.441	0.66170

The range of the residuals of this model are in Table 3 and show a very wide range from -332 to 300. This is a large range and shows that the heartwood area is not being measured precisely and another model is needed to try and reduce the residual range. Table 4 shows the residual standard error is 164.6 cm^2, which is very large. The R^2 value is 0.81, which means there is a strong positive correlation between observed heartwood area and predicted heartwood area, which is a similar result to other studies (Benson et al., 2019). Having site as a fixed variable is significant in the model as the P-value is less than 0.05.

Table 3 Residual range from model 1

Residuals:				
Min	**1Q**	**Median**	**3Q**	**Max**
-332.4	-92.81	-12.24	111.18	300.56

Table 4 Summary outputs from model 1

Coefficients:				
	Estimate Std.	**Error**	**t value**	**Pr(>|t|)**
(Intercept)	32.4465	52.1225	0.623	0.537
Heartwood_area_ERT	0.6686	0.1176	5.686	1.67E-06
Site	381.4883	65.148	5.856	9.85E-07
Residual standard error: 164.6 on 37 degrees of freedom				
Multiple R-squared:	0.8168		**Adjusted R-squared:**	0.8069
F-statistic:	82.48 on 2 and 37 DF		**p-value:**	2.315e-14

When plotting the residuals from this initial model there is non-constant variance, known as variance heterogeneity. This means that the values are not randomly scattered, and variance increases with increasing estimates of heartwood area, and there is a clear difference between the two environments. Figure 9 shows that the Welcome Bay site values have a larger spread in the residuals. In further models it was important to try and reduced the separation between the two environments and reducing the range of residual values.

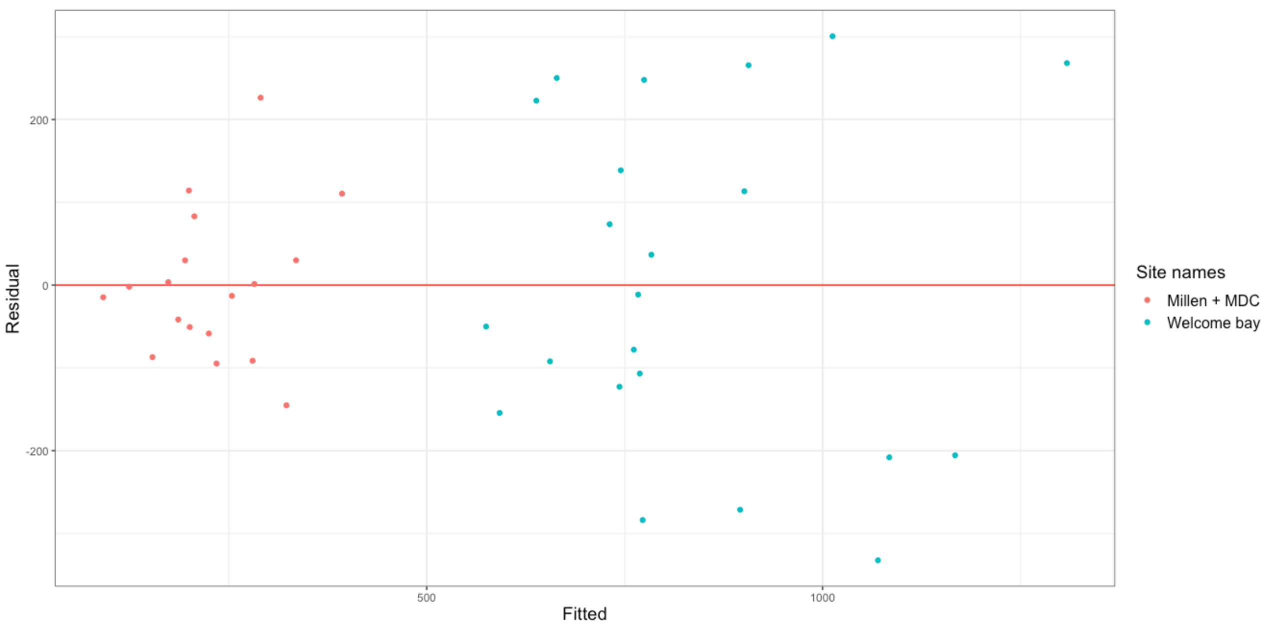


Figure 9: Plotting first model residuals against fitted values.

Model 2

The second model was a follow on from the first model and was an attempt to model the heterogeneity present in the results. It did this by using generalized least squares, which allows the errors to be correlated and have unequal variances which are shown in model 1. The output of this model shown in Table 5, shows that the standardized residuals have a much smaller range than model 1. This model did not improve the residual standard error (165.3 cm^2). From the correlation of factors, there appears to be a moderate negative correlation between site and predicted heartwood area. From this model, it is clear that further modelling was required to reduce the standard error that is present in the result.

Table 5 summary output from model 2

AIC		**BIC**	**logLik**		
	498.391	506.4455	-244.1955		
Coefficients:					
		Value	**Std.Error**	**t-value**	**p-value**
(Intercept)		10.7274	29.60268	0.362379	0.7191
Heartwood_area_ERT		0.7304	0.11929	6.123095	0
Site		373.6145	47.42212	7.878486	0
Correlation:					
		(Intr)	**H__ERT**		
Heartwood_area_ERT		-0.799			
Site		0.262	-0.611		
Standardized residuals:					
	Min	**Q1**	**Med**	**Q3**	**Max**
	-1.66205549	-0.7230009	-0.0429374	0.5403994	2.07507818
Residual standard error: 159.032					

The residuals plotted against fitted values for the second model are shown in Figure 10. When compared to the first model the scatter of the residuals is slightly less, and the two environments appear to be a closer together, however, there still appears to be variance heteroscedasticity.

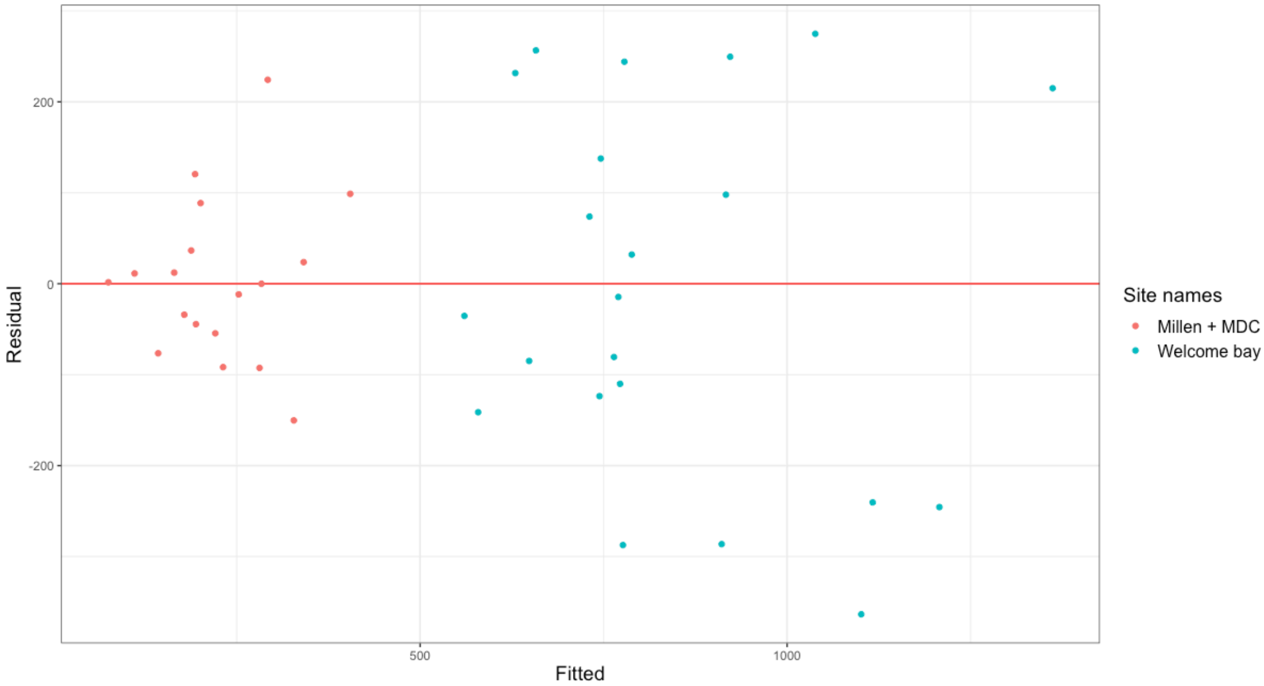


Figure 10: Plotting second model residuals against fitted values.

To compare the first two models an ANOVA was used. This showed that in fact, the two models were different from each other as the P-value was less than 0.05. The results from this that the second model was a better fit. This means that modelling the heteroscedasticity that is present is a good option to improve the fit of the model, but these models do not improve the standard error and cannot be used to calibrate estimated values. However, there is still room for improvement in a model to improve the fit of the predicted heartwood area.

Table 6 ANOVA output of model 1 and model 2

	Model	df	AIC	BIC	logLik	Test	L.Ratio	p-value
Model 1	1	4	511.12	517.56	-251.56			
Model 2	2	5	498.39	506.45	-244.20	1 vs 2	14.73	1E-04

Model 3

The third model was a mixed effect model which includes the factors; site, measurement height, and tree height as fixed effects. Tree ID and site were used as random effects to see if it would improve the fit of the model to aid in a calibration method. From Table 7 it is clear that using tree ID as a random effect in the model considerably improved the fit of the model as the standard error was 46.8 cm^2. There appeared to be a correlation between the predictor factors, such as tree height and site, and between the two different measurement heights. The result of this correlation means not all of these factors need to be included in the final model.

Table 7 Summary output of model 3

AIC	**BIC**	**logLik**			
453.4904	467.2276	-217.7452			
	(Intercept)	**Residual**			
StdDev:	147.539	46.84751			

	Value	**Std.Error**	**DF**	**t-value**	**p-value**
(Intercept)	-459.2031	207.49944	17	-2.213033	0.0409
Heartwood_area_ERT	0.4352	0.09036	17	4.815848	0.0002
Tree_height	30.0719	12.75075	16	2.358446	0.0314
HeightDBH	69.2255	57.81351	17	1.197393	0.2476
HeightGround	130.4676	59.9551	17	2.176088	0.0439
enviroWelcomebay	38.5831	187.66313	1	0.205597	0.8709

Correlation:	**(Intr)**	**H__ERT**	**Tr_hgh**	**HghDBH**	**HghtGr**
Heartwood_area_ERT	0.162				
Tree_height	-0.93	-0.25			
HeightDBH	-0.327	-0.091	0.078		
HeightGround	-0.35	-0.279	0.126	0.948	
enviroWelcomebay	0.804	0.077	-0.918	-0.072	-0.086
Standardized Within-Group Residuals:					
	Min	**Q1**	**Med**	**Q3**	**Max**
	-1.41185473	-0.44271044	0.01683891	0.42831722	1.21799458

The ANOVA of model 3 confirms the results above that site is not significant in the model. Therefore, tree height should be used as a predictor factor only, as site as a fixed effect does not add to the fit of the model.

Table 8 ANOVA summary of model 3

	numDF	denDF	F-value	p-value
(Intercept)	1	17	272.64056	<.0001
Heartwood area ERT	1	17	136.60433	<.0001
Tree height	1	16	32.41776	<.0001
Measurement Height	2	17	6.1986	0.0095
Site	1	1	0.04227	0.8709

The residual values plotted against the fitted values, shows an improvement from model 2. The range of the residual is also much less, with a range between -50 and 50. This means that using tree ID as a random effect improved the fit of the model, and can be used to calibrate the predicted heartwood area.

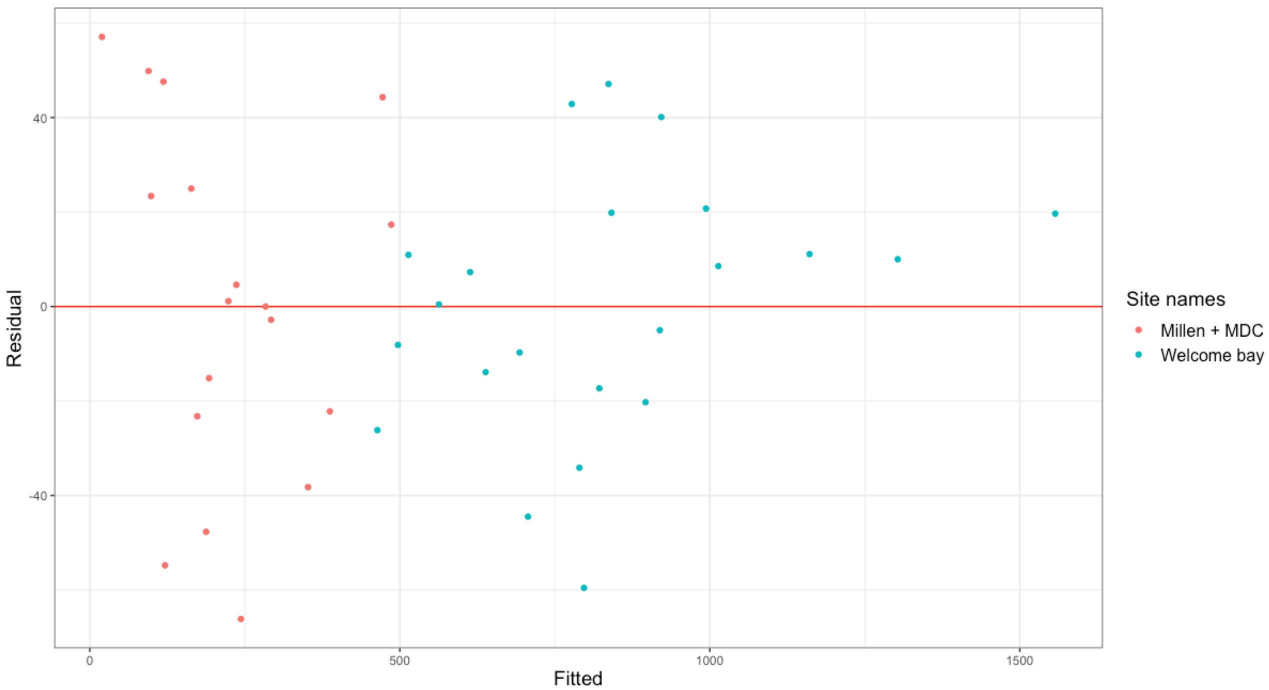


Figure 11: Plotting third model residuals against fitted values.

Model 4

The fourth model was a continuation of the third model with site removed as a fixed effect from the model and only measurements at DBH. Tree ID and site were still used as random effects in this model. The range of standardized residuals was the smallest of all the models tried with a standard error of only 1.2 cm^2. This model was the most robust and is the best method to fit the error present in the predicted heartwood area. To test how the random effects influence the model, site was removed, and the standard error inflated to 54.0 cm^2. Therefore, without site, the model produces bias within sites.

Table 9 Summary output of model 4

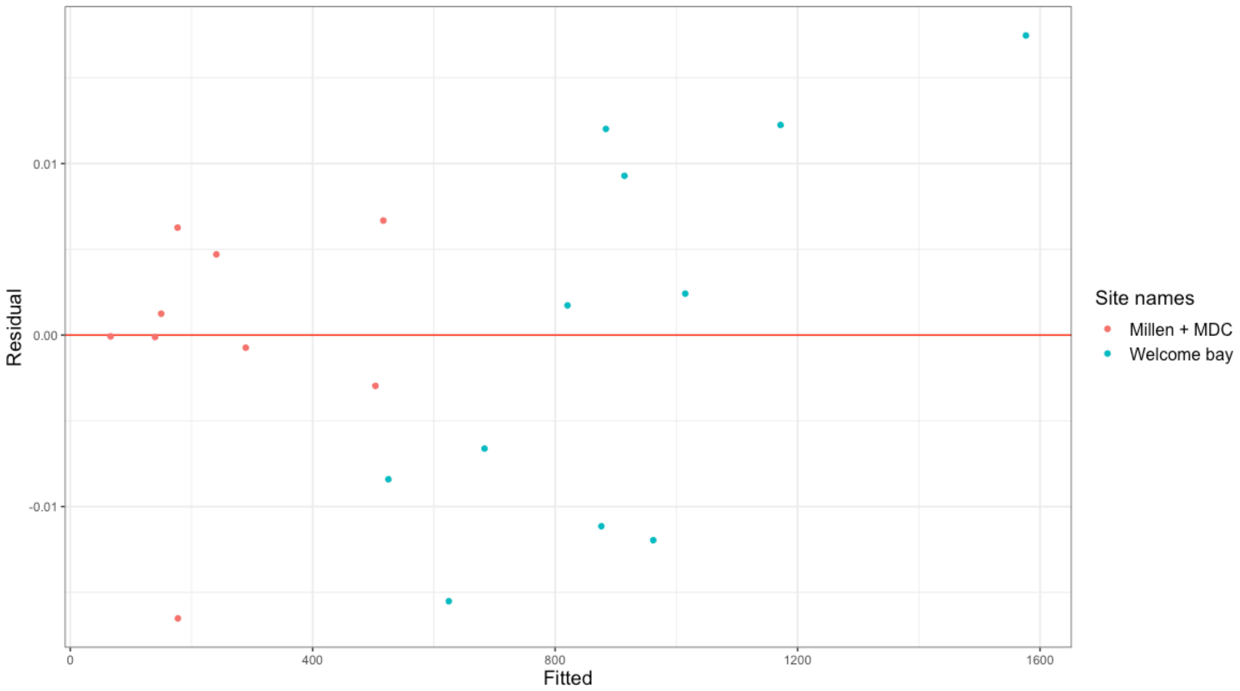
AIC	**BIC**	**logLik**			
255.2518	260.2511	-121.626			
	(Intercept)	**Residual**			
Standard error	153.8236	1.24162			
	Value	**Std.Error**	**DF**	**t-value**	**p-value**
(Intercept)	-405.672	112.4906	15	-3.60628	0.0026
Heartwood_area_ERT	0.4748	0.15851	15	2.995127	0.0091
Tree_height	33.4253	6.56664	15	5.090175	0.0001
Correlation:					
	(Intr)	**H__ERT**			
Heartwood_area_ERT	0.208				
Tree_height	-0.794	-0.72			
Standardized Within-Group Residuals:					
Min	**Q1**	**Med**	**Q3**	**Max**	
-0.013307533	-0.00569	0.000471	0.0051287	0.01407	

The outputs from an ANVOA of model 4 shows that using tree height as a fixed effect is a good option for calibrating the model and reduces the F-value in predicted heartwood area compared with the results from the other models in this analysis.

Table 10 ANVOA summary of model 4

	numDF	**denDF**	**F-value**	**p-value**
(Intercept)	1	15	320.437	<.0001
Heartwood_area_ERT	1	15	92.0668	<.0001
Tree_height	1	15	25.9099	1.00E-04

When plotting the residuals against the fitted values in model 4, they appear to be randomly scatted, with no clear trends, apart from a slight flaring of values at the beginning. Model 4 has the best fit out of any of the other models used in this analysis. This would be the preferred model to calibrate the predicted heartwood area values.



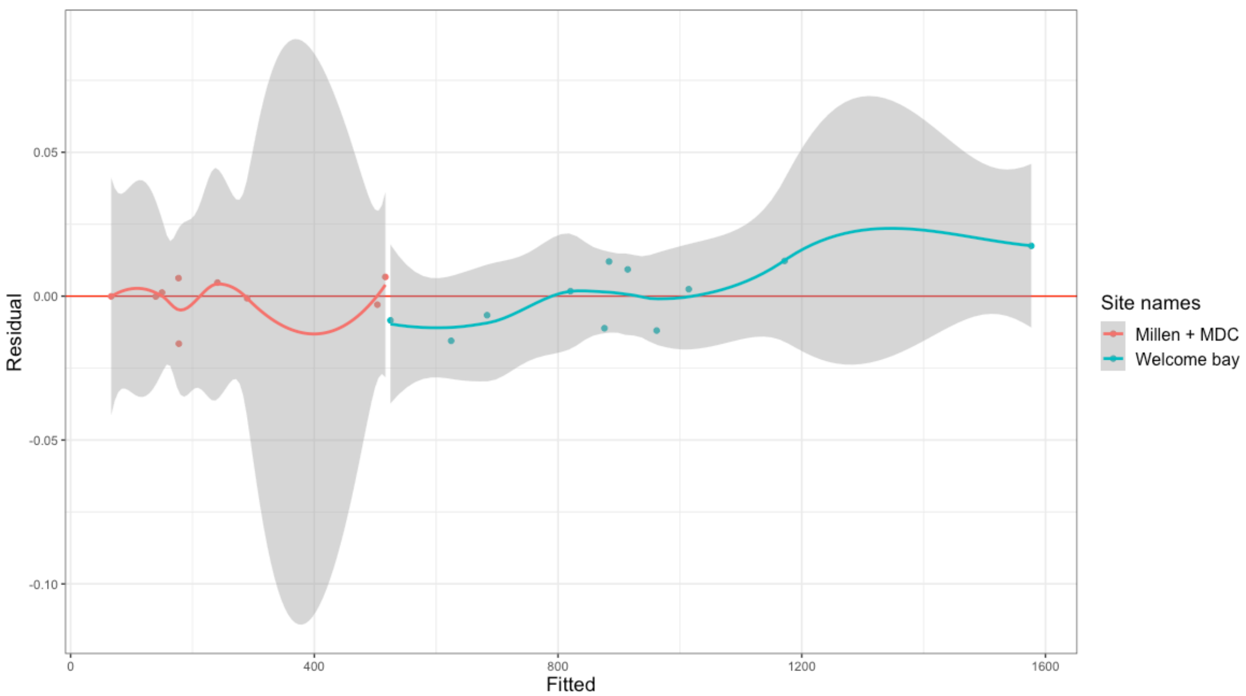


Figure 12: Plotting fourth model residuals against fitted values, without and with smooth line.

6. Conclusion and Recommendation

6.1 Conclusion

From the results of this analysis, there is a clear bias in the predicted heartwood area from the ERT measurements. The bias is both positive and negative depending on the site, tree size, or climate, and there is no way of telling if the prediction is going to be overestimated or underestimated before measurements takes place. However, from the results as there is a strong correlation between predicted heartwood area and actual heartwood area, but the relationship varied with site. The standard error from a model including all these effects was 1.2 cm^2 on a range of predictions from 60 to 1,600 cm^2. If you remove site or tree as a random effect it inflated the standard error to 54 cm^2 if you remove site, and it produces bias between sites. Site and tree height were correlated, and an analysis of their contributions to the model suggested that only tree height should be included in the model. Measurement heights made no difference to the relations between actual heartwood area and ERT estimates, therefore only DBH was included in the final model.

There were a number of different climate factors between the sites that could have influenced the results; air temperature, humidity, ground moisture content. It is unknown whether or not these factors influenced the results, but they may have had an effect.

Another reason why this method of measuring heartwood area may not be ideal is due to the time taken for each ERT scan compared with taking cores from each tree. With an average scan time of 15 minutes per tree with one person taking the measurement, and with one study showing it is faster and more efficient with two people (Baláš et al., 2020). Taking cores samples would take less time to survey an entire stand and fewer people compared with taking ERT measurements.

The result differs from other studies completed using this measurement technique on different species which concluded that the ERT was an accurate measurement method. This illustrates the importance to undertake this type of research with each desired species as the properties of each species can be different and this will likely influence the results.

6.2 Recommendation

The results show that there is difference between the sites and tree sizes, however, it is not completely clear whether site, tree size, climate, or a mixture of all these factors is the reason for the bias evident in the results. Residuals in the zone of overlap in tree size between sites suggests strongly that site, rather than tree size produced the bias, however. For each site, the results from the TreeTronic would need to be calibrated independently. This calibrated value will also need to be updated depending on the climatic conditions of a site at time of measurement.

From this analysis, it would not be recommended to use ERT with the TreeTronic to measure heartwood area in *E. globoidea* due to bias. Further measurement work would need to be undertaken in order to develop an overall calibration method depending on the factors that may influence error in heartwood prediction, such as tree size, site location, and current climate of the measurement period. Measurement points would need to be recorded in different climates from the same site (summer and winter) to determine the size of the effect climate has on results. Measurements would also need to be taken from the same trees over a number of years, or from a range of tree sizes at the same site to determine how tree size influences the results. Finally, a larger range of sites would need to be measured to find the relationship site has on the measured value.

Until further study can be completed, it would be recommended to continue with current destructive methods of measuring heartwood area, such as core sampling or felling and cross-sections removed with samples stained to identify heartwood.

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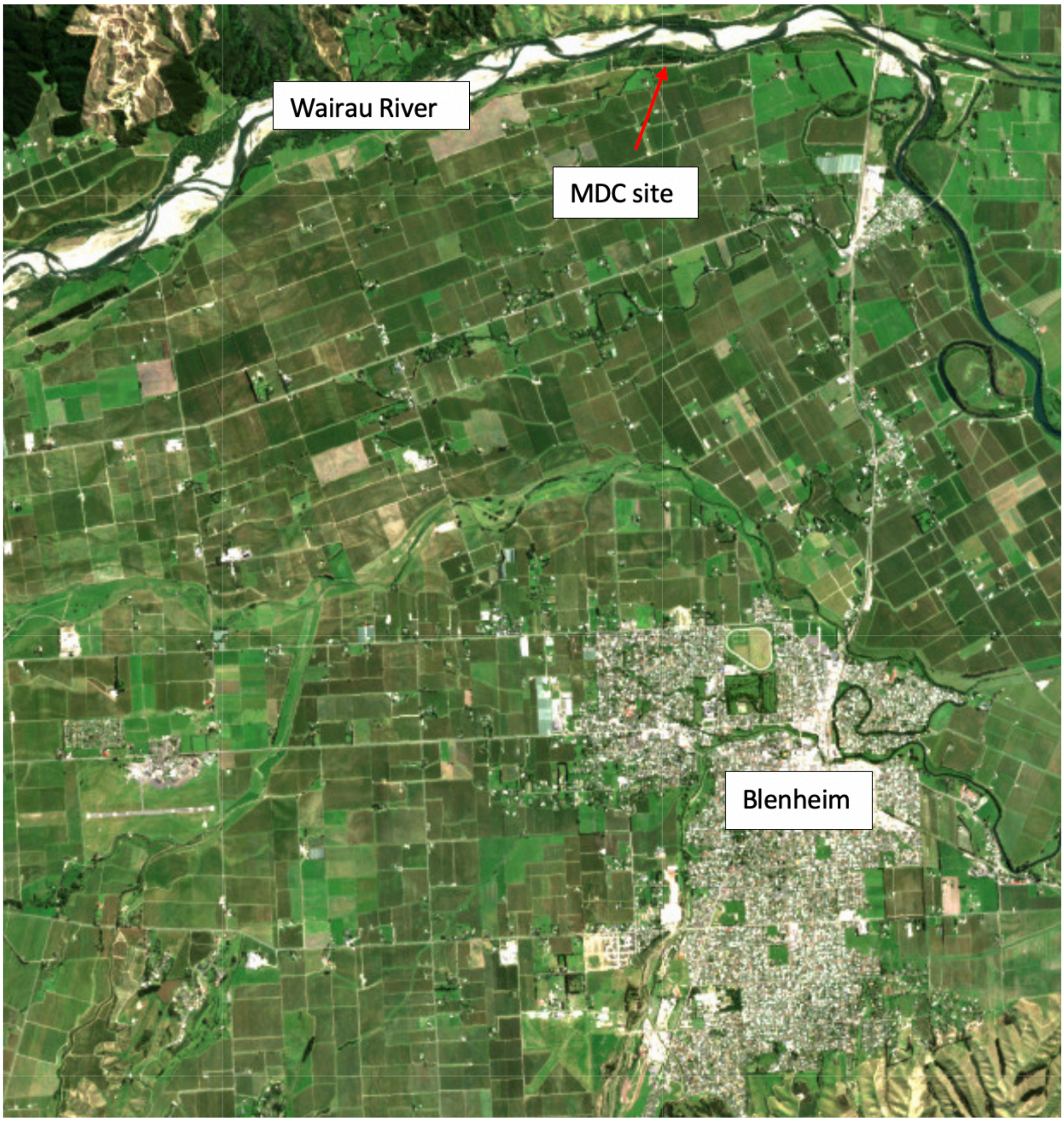
Appendices

Appendix 1

Appendix 1.1: Location of Millen site.

Appendix 1.2: Location of MDC site.



Appendix 1.3: Location of Welcome Bay site.